

Diffusion in Concert halls analyzed as a function  
of time during the decay process

Claus Lynge Christensen  
&  
Jens Holger Rindel  
Odeon A/S, Lyngby, Denmark

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# Agenda

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- Why investigate diffusivity?
- Directional Diffusion and Steady State Diffusivity
- Defining the Dynamic Diffusion Curve (DDC)
- Normalising the DDC
- Typical features of the DDC
- DDC in (models of) 12 concert halls
- DDC as a function of distance in 2 halls
- DDC and flutter echo
- Conclusions

## Motivation, why investigate diffusivity?

- Diffusivity is assumed to be important for the quality of concert halls
- Efforts are put into promoting diffuse reflections;
  - making surfaces scatter sound
  - shape of geometry
  - distribution of materials

Therefore we should understand better how given designs affect diffusivity in rooms.

## Steady State Diffusivity

Thiele (1953) defined Directional Diffusion ( $d$  in %) as

$$d = \left(1 - \frac{\mu}{\mu_0}\right) \times 100\% = \frac{E - I}{E} \times 100\%$$

where  $E$  is sound energy and  $I$  is sound intensity

Directional Diffusion is usually close to 100%, so instead we may prefer to define Steady State Diffusivity in dB as:

$$D(ss) = 10 \times \log_{10}(E) - 10 \times \log_{10}(I) \quad [\text{dB}]$$

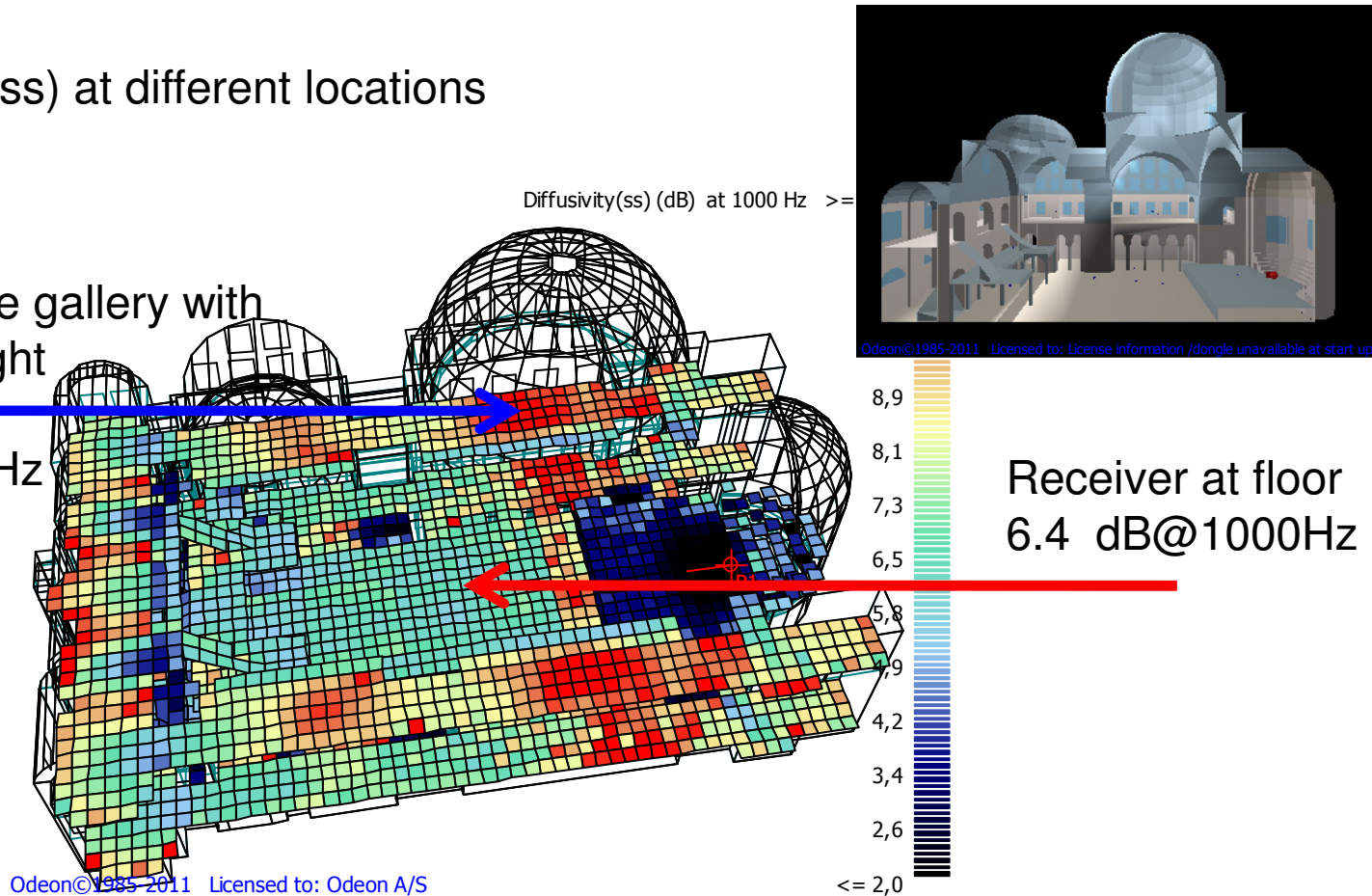
Note!  $I = \sqrt{I_{8x}^2 + I_{8y}^2 + I_{8z}^2}$

# Steady State Diffusivity

Example on  $D(ss)$  at different locations

Receiver in side gallery with  
no visible no sight

19.2 dB@1000Hz



# Dynamic Diffusivity Curve – DDC energy and intensity curves

Backwards integrated squared impulse response curve

$$E(t_n) = 10 \times \log_{10} \int_{t=\infty}^{t=t_n} E(t) dt \quad [dB]$$

Backwards integrated intensity curve

$$I(t_n) = 10 \times \log_{10} \sqrt{\left( \int_{t=\infty}^{t=t_n} I(t)_{8x} dt \right)^2 + \left( \int_{t=\infty}^{t=t_n} I(t)_{8y} dt \right)^2 + \left( \int_{t=\infty}^{t=t_n} I(t)_{8z} dt \right)^2}$$

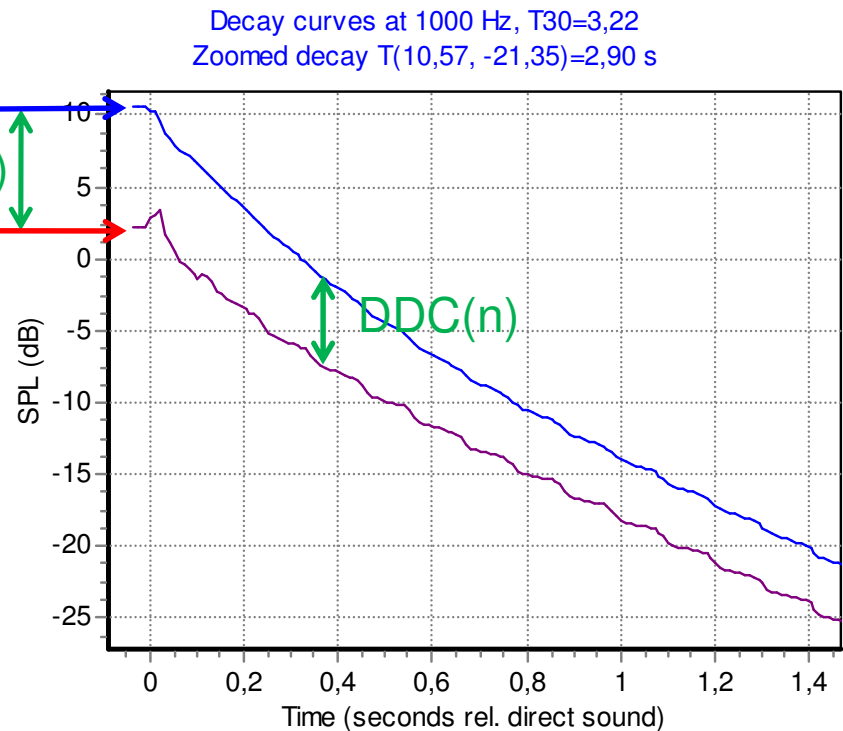
# Dynamic Diffusivity Curve – DDC example; energy and intensity curves

Schröder curve

Backwards integrated  
Intensity curve

$D(ss)$

DDC(n)



- E, Simulated
- E, Integrated
- E, Corrected
- I, Simulated
- I, Integrated

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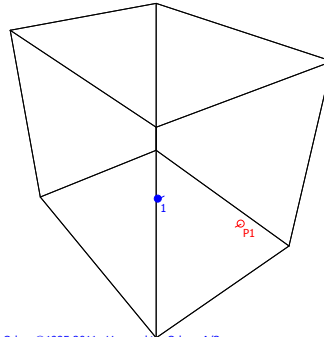
## Dynamic Diffusivity Curve – DDC

DDC is the difference between energy and intensity curves

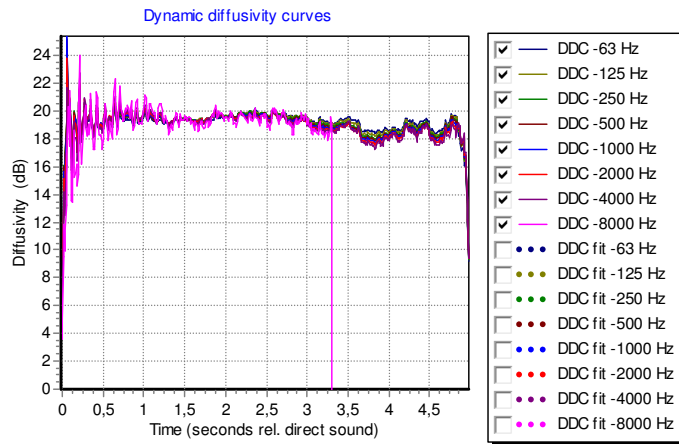
$$\begin{aligned} DDC(n) &= E(n) - I(n) \\ &= 10 \times \log_{10} \int_{t=\infty}^{t=t_n} E(t) dt \\ &\quad - 10 \times \log_{10} \sqrt{\left( \int_{t=\infty}^{t=t_n} I(t)_{8x} dt \right)^2 + \left( \int_{t=\infty}^{t=t_n} I(t)_{8y} dt \right)^2 + \left( \int_{t=\infty}^{t=t_n} I(t)_{8z} dt \right)^2} \quad [\text{dB}] \end{aligned}$$

# Comparing DDC for rooms with different T30

Box shaped room 12 x 14 x 16

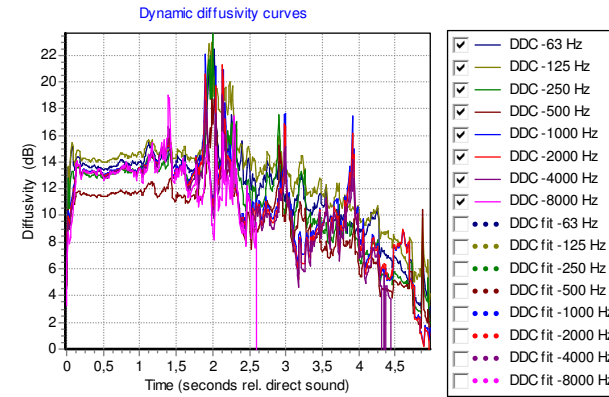


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T30=3.24s@1000 Hz  
 All hard surfaces  
 Low scattering

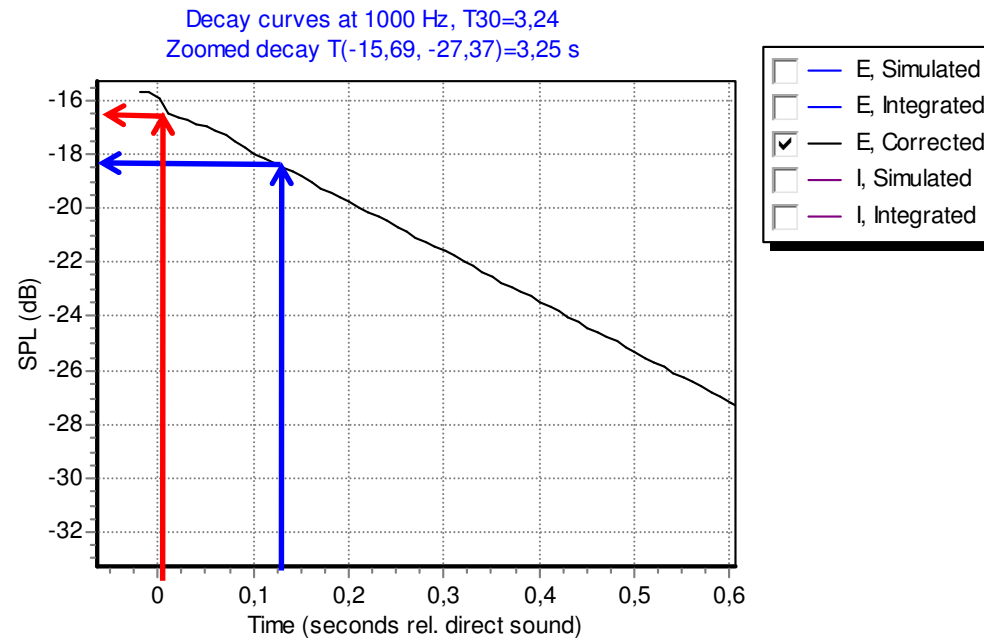


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T30=1.65s@1000 Hz  
 hard surfaces+absorbing ceiling  
 High scattering

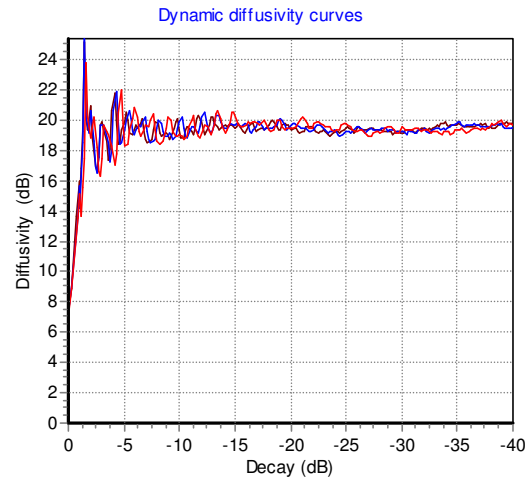
# Normalising DDC

- Use Schröder curve for normalization
- Substitute time axis with decay [dB]

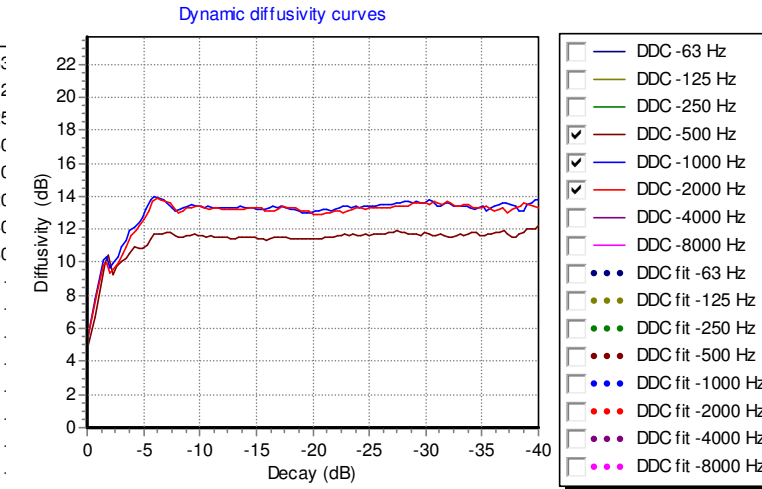


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# Normalising DDC



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$T_{30}=3.24s@1000\text{ Hz}$   
 All hard surfaces  
 Low scattering

$T_{30}=1.65s@1000\text{ Hz}$   
 hard surfaces+absorbing ceiling  
 High scattering

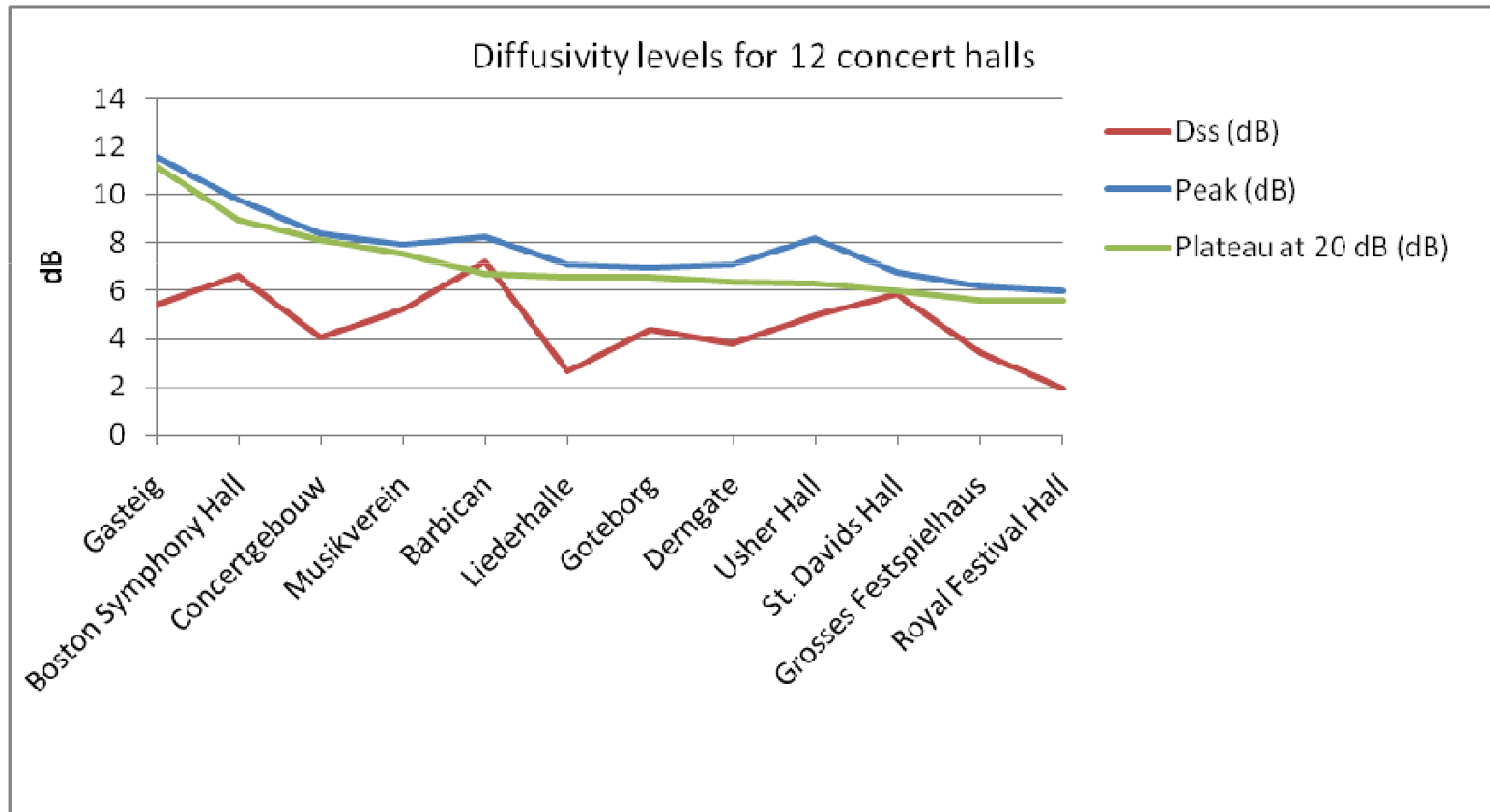
## Typical features of DDC

- Initial value  $D_{ss}$  is lower than later values
- A peak appears within the first 5 (to 10) dB
- DDC reaches its plateau level after some 5 to 10 dB decay
- The plateau can have ripples e.g. in case of a flutter echo

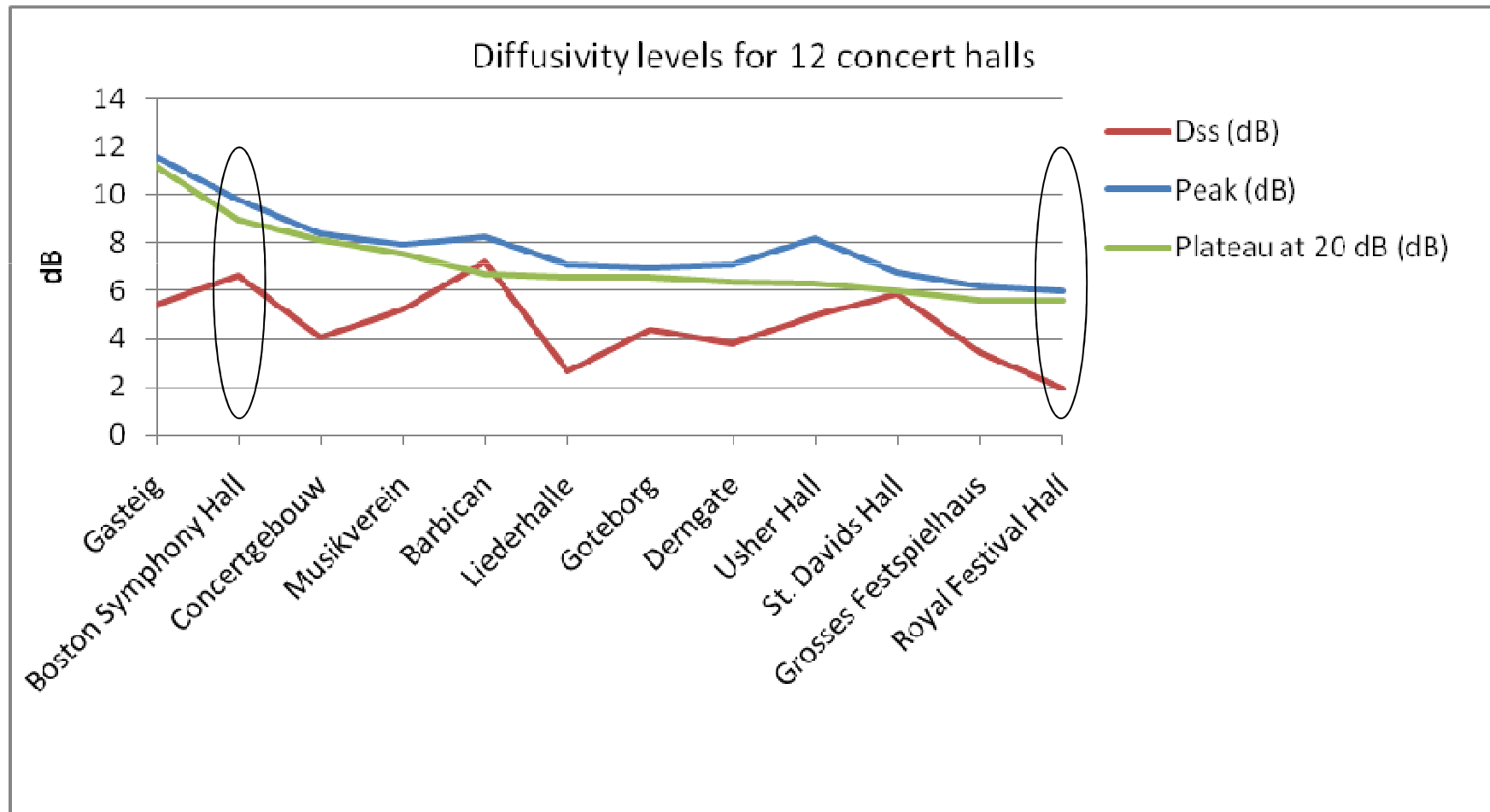
# 12 Concert halls (models)

## Source mid stage – receiver mid-parterre

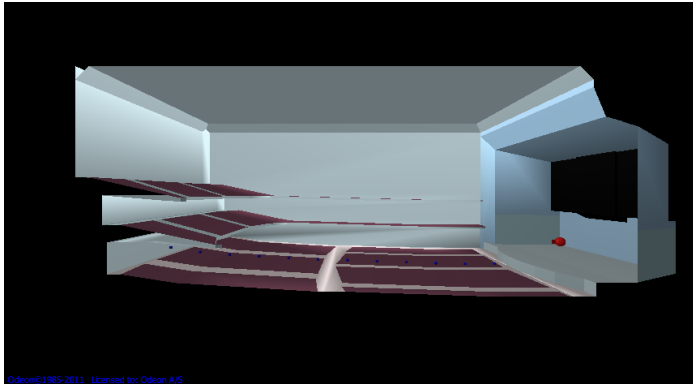
### Dss, Peak and Plateau levels



# Two examples for comparison



# Diffusivity(Dss) – Boston Symphony Hall

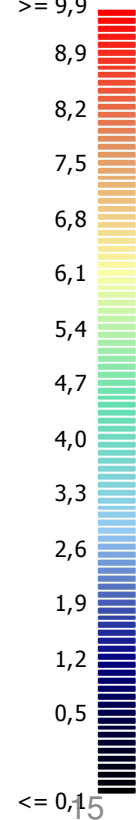
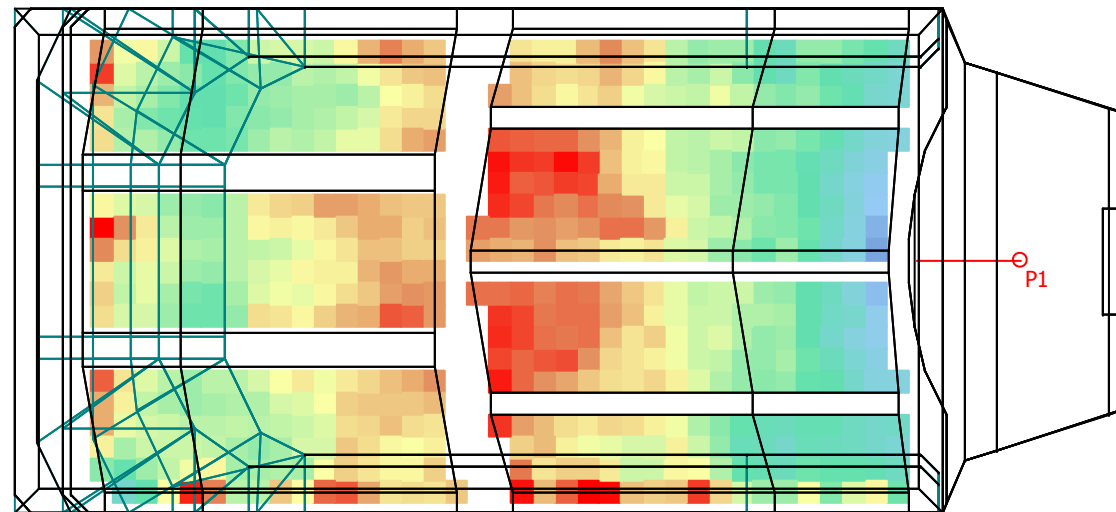


Floor level, only

20 30 40 metres

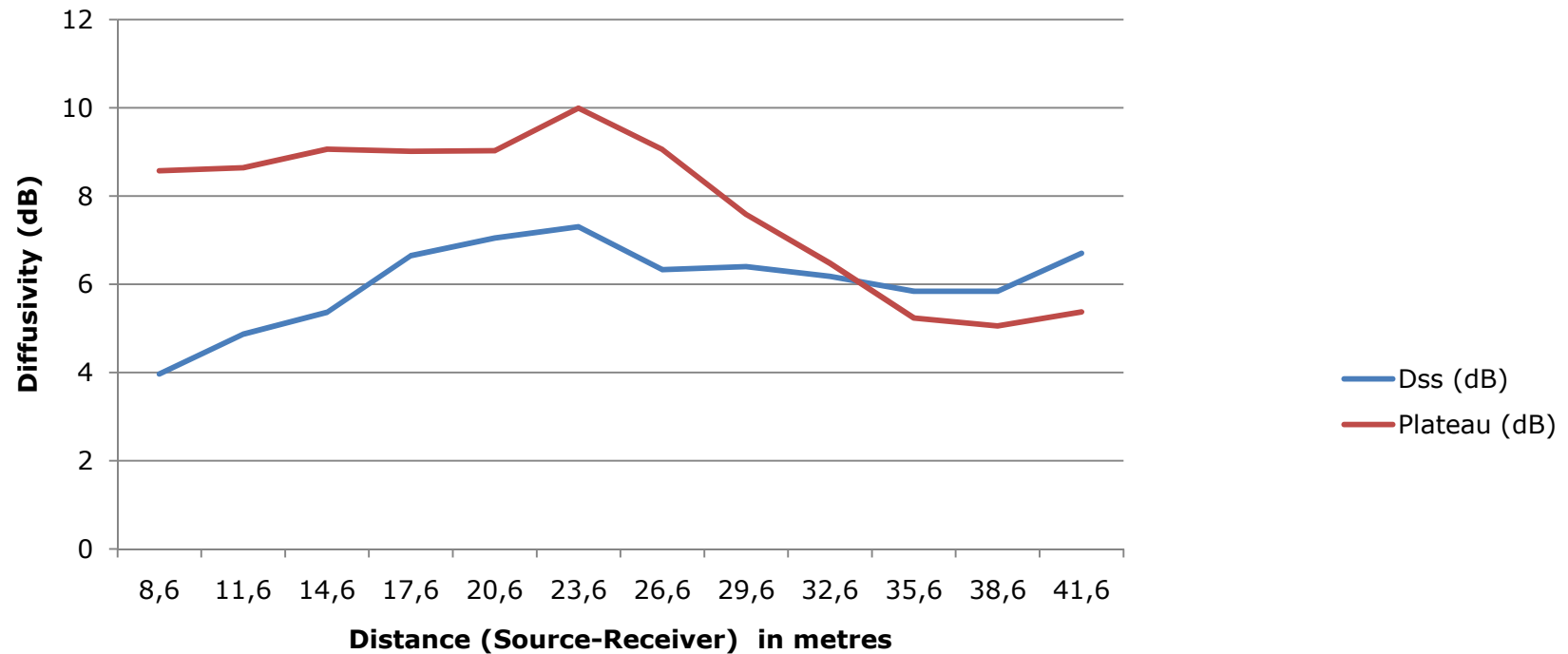
Diffusivity(total) (dB) at 1000 Hz  $\geq 9,9$

25 metres  
20  
15  
10  
5  
0

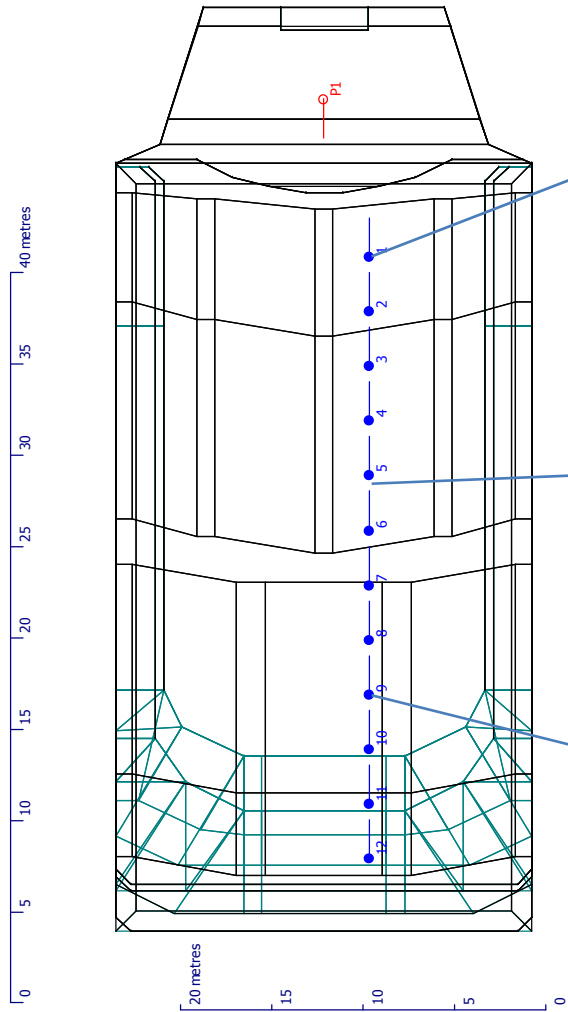


# Dss and Plateau levels as a function of distance

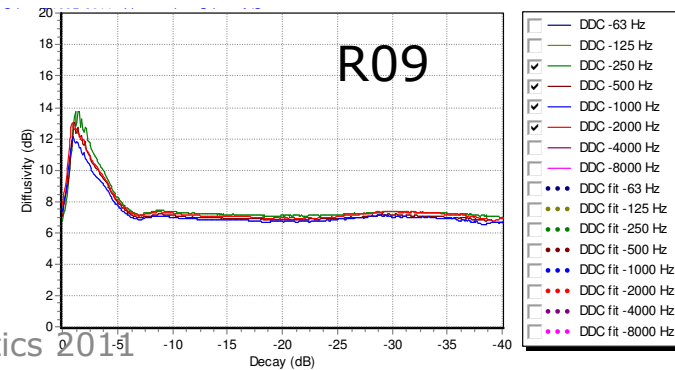
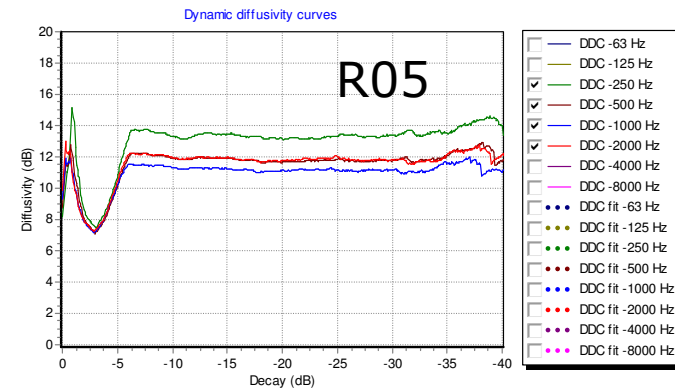
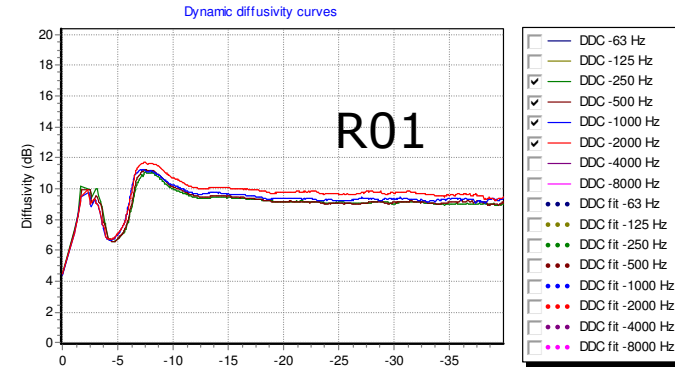
## Boston Symphony Hall



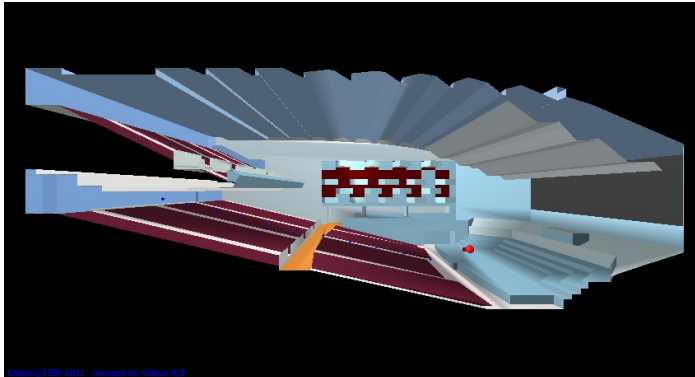
# DDC variation with distance in BSH



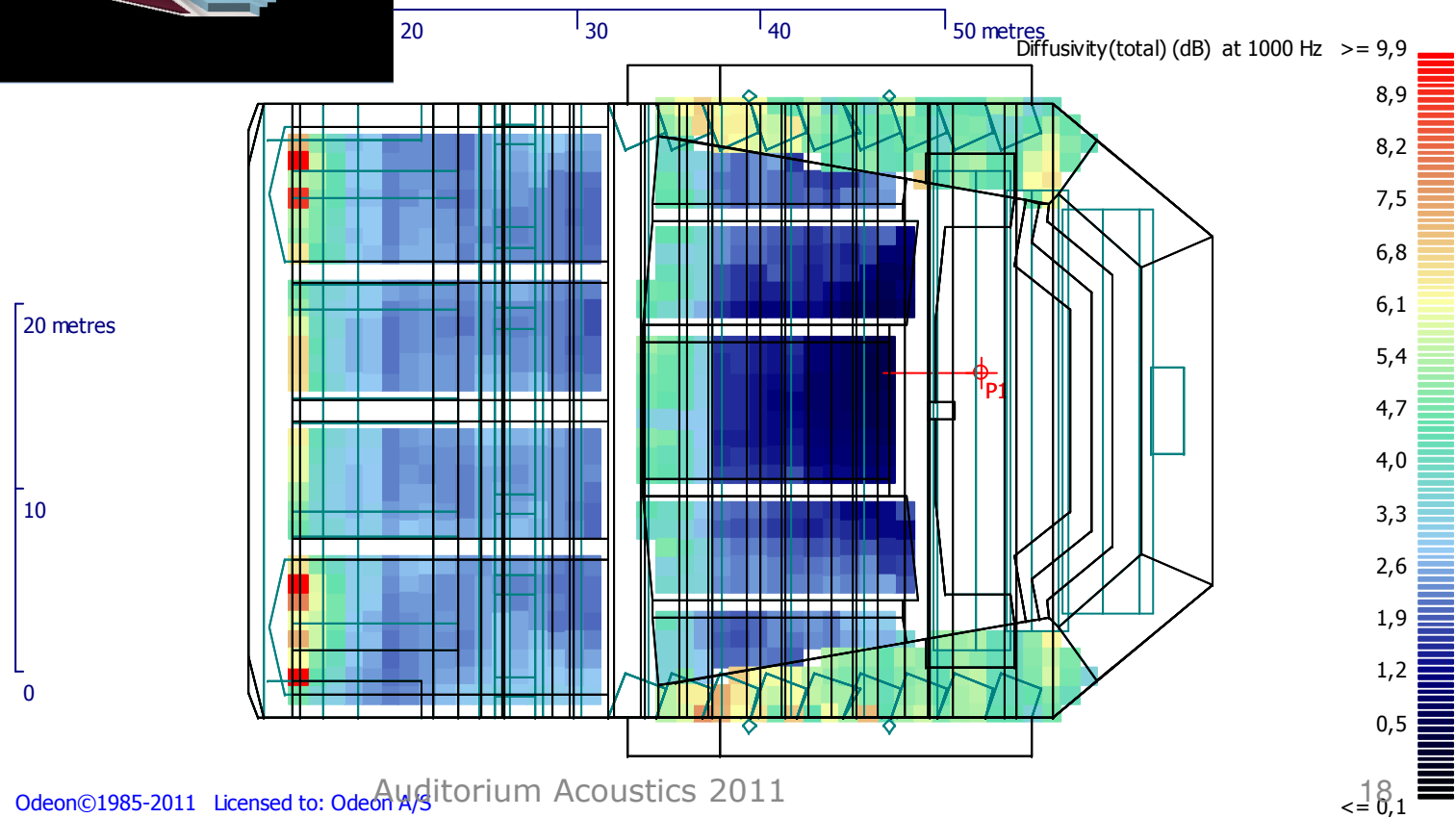
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# Diffusivity(Dss) – Royal Festival Hall

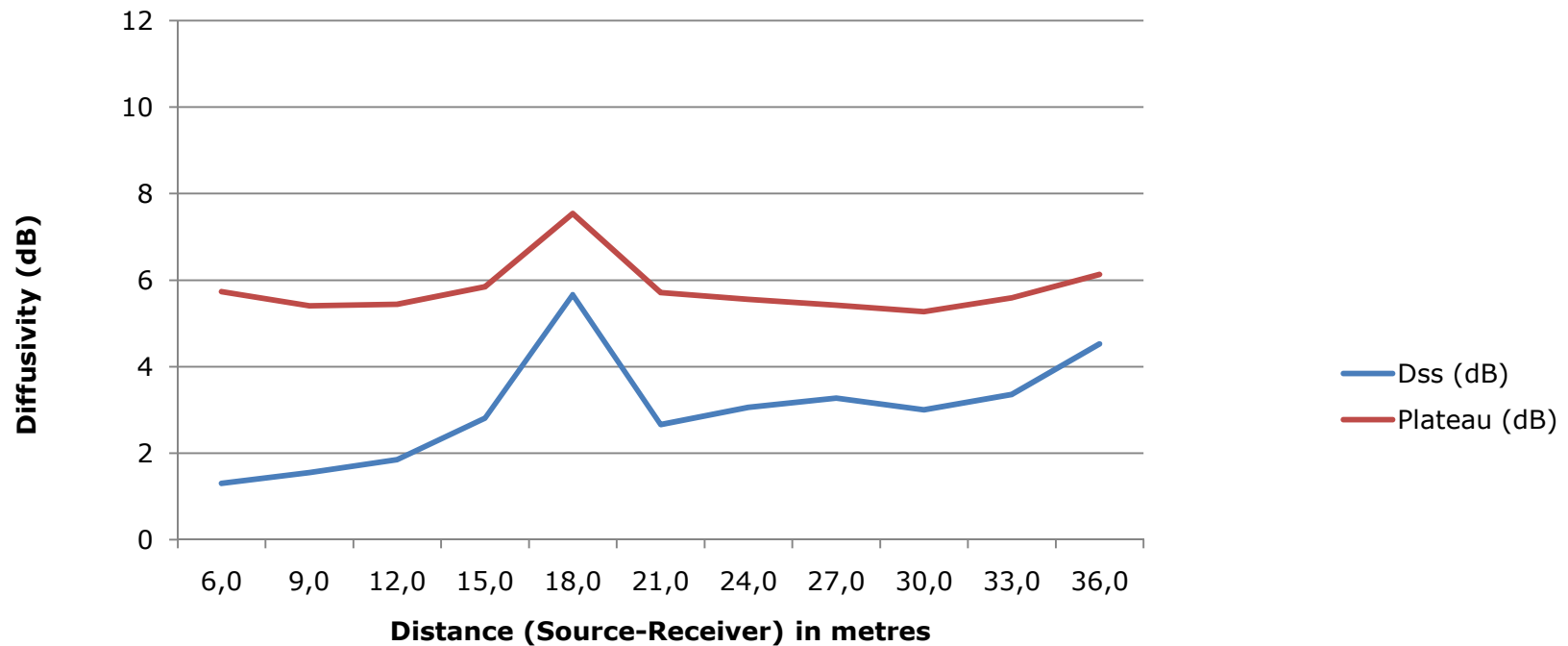


Floor level, only

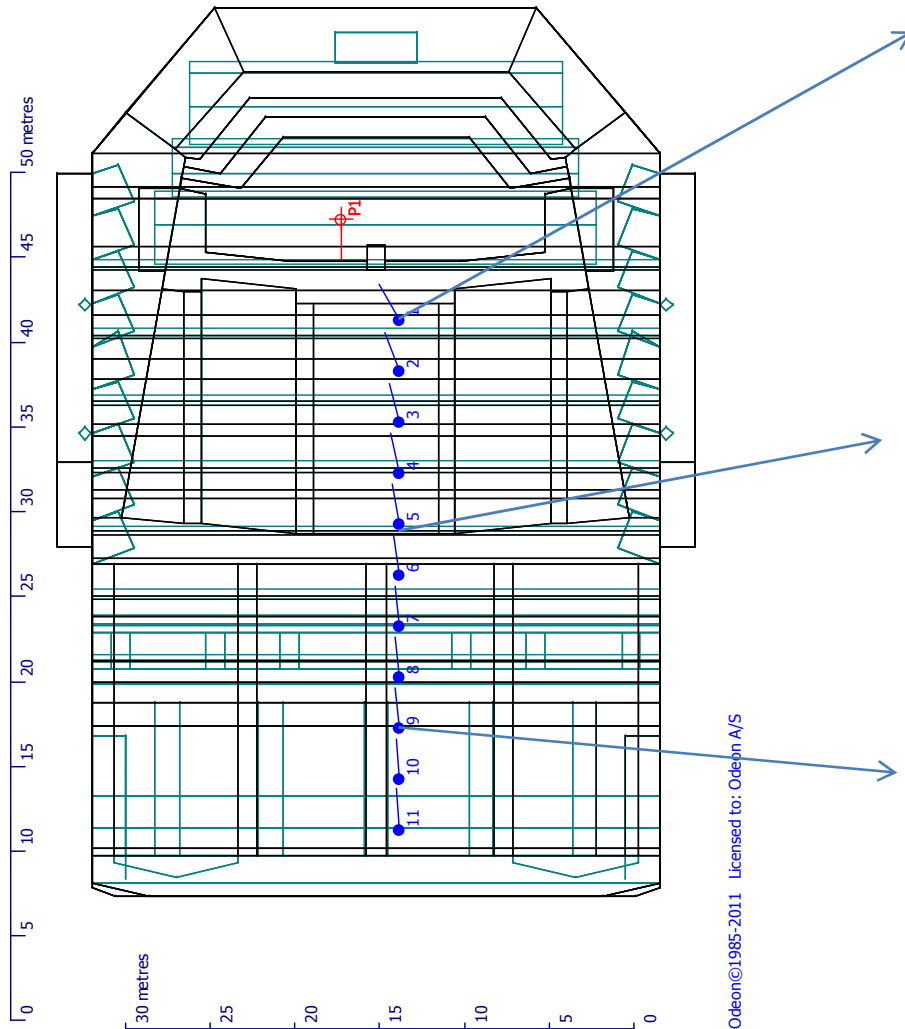


# Dss and Plateau levels as a function of distance

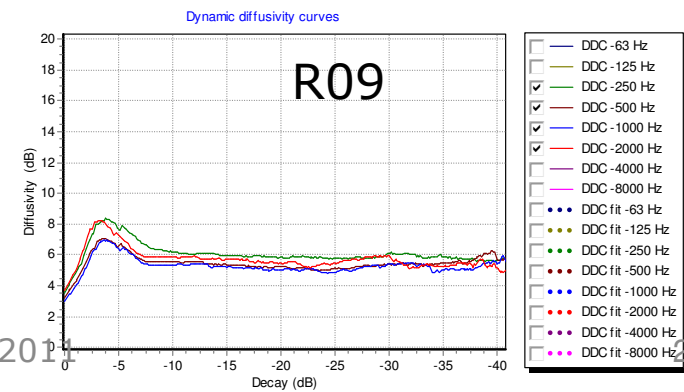
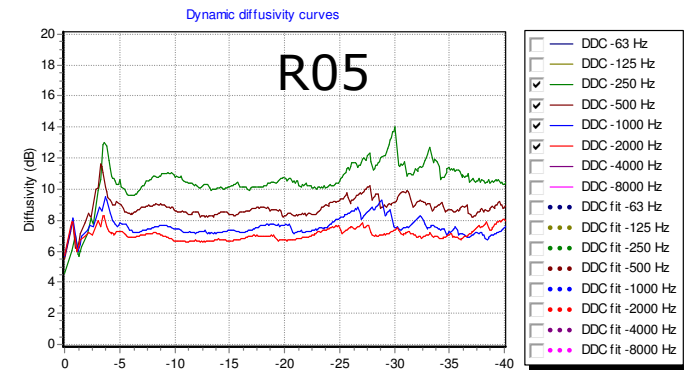
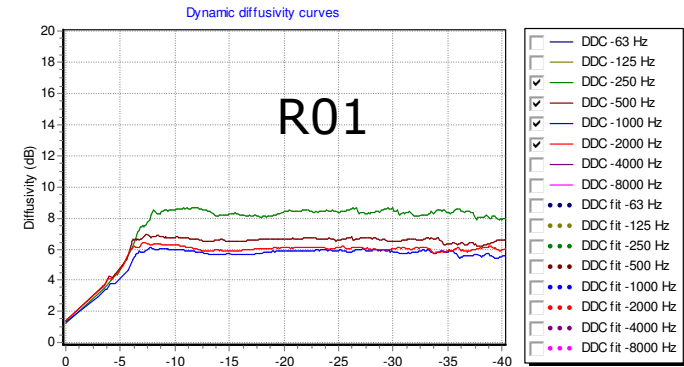
## Royal Festival Hall



# DDC variation with distance in RFH

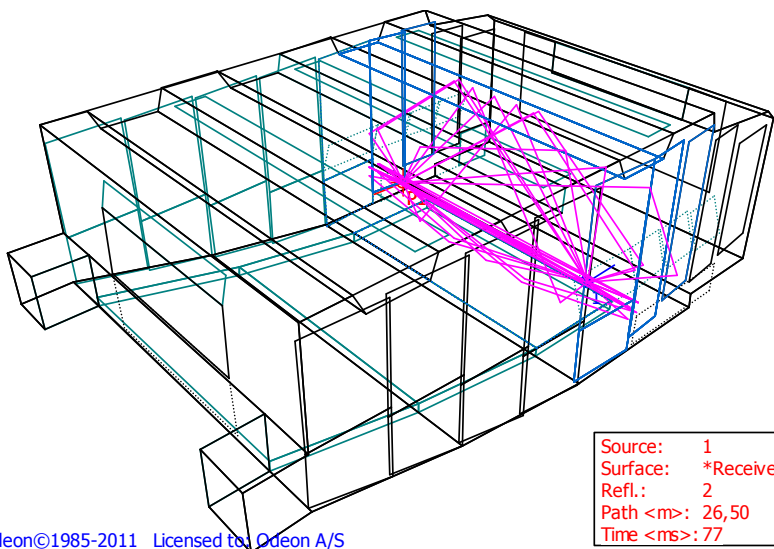


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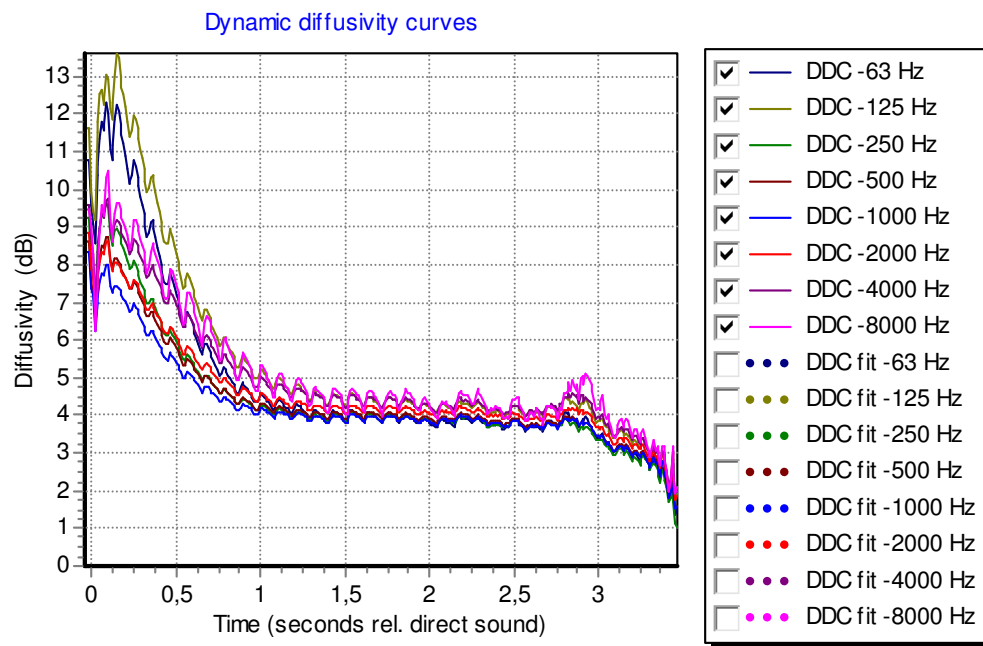
# DDC and Flutter Echo

## Queen's Hall, Copenhagen



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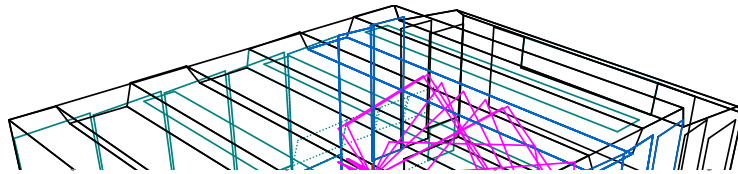
4 reflector panels tilted slightly inwards – creating a flutter echo



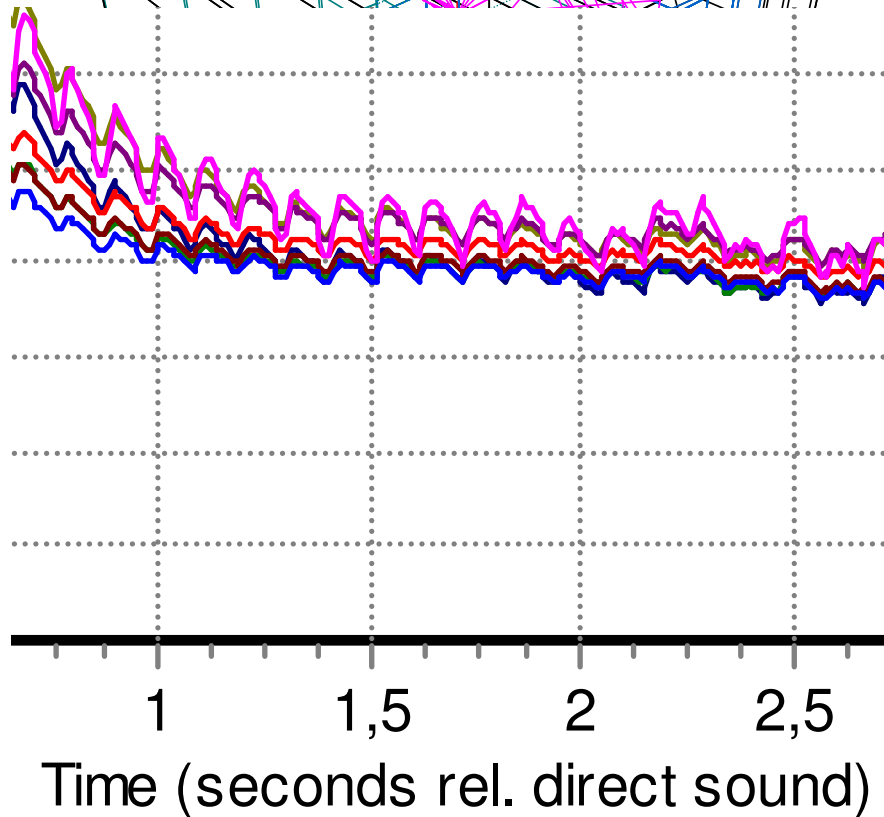
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# DDC and Flutter Echo

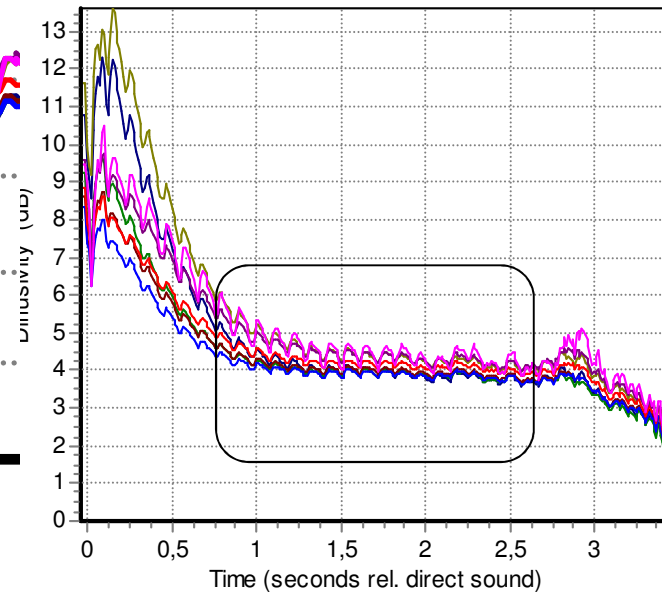
## Queen's Hall, Copenhagen



4 reflector panels tilted slightly inwards – creating a flutter echo



Dynamic diffusivity curves

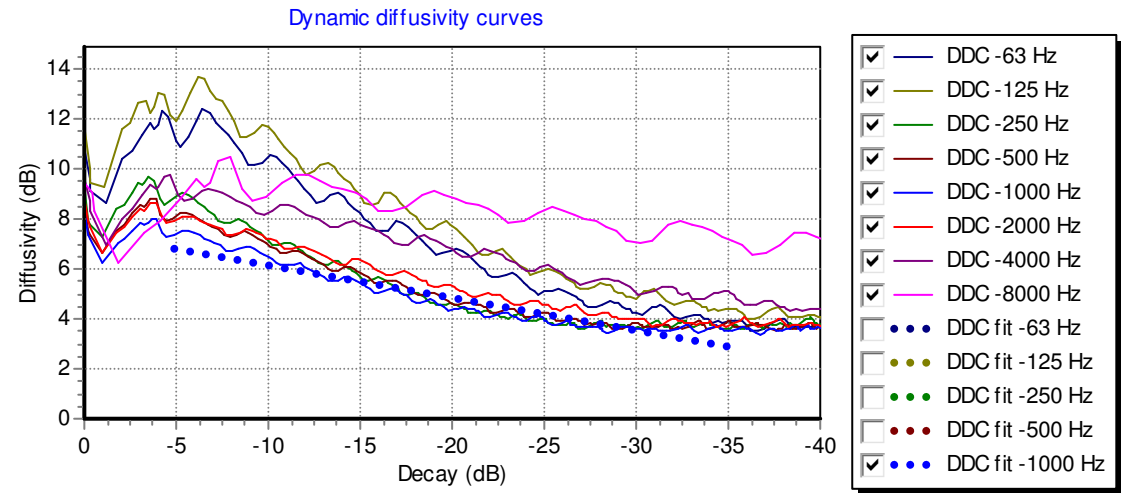


- DDC -63 Hz
- DDC -125 Hz
- DDC -250 Hz
- DDC -500 Hz
- DDC -1000 Hz
- DDC -2000 Hz
- DDC -4000 Hz
- DDC -8000 Hz
- DDC fit -63 Hz
- DDC fit -125 Hz
- DDC fit -250 Hz
- DDC fit -500 Hz
- DDC fit -1000 Hz
- DDC fit -2000 Hz
- DDC fit -4000 Hz
- DDC fit -8000 Hz

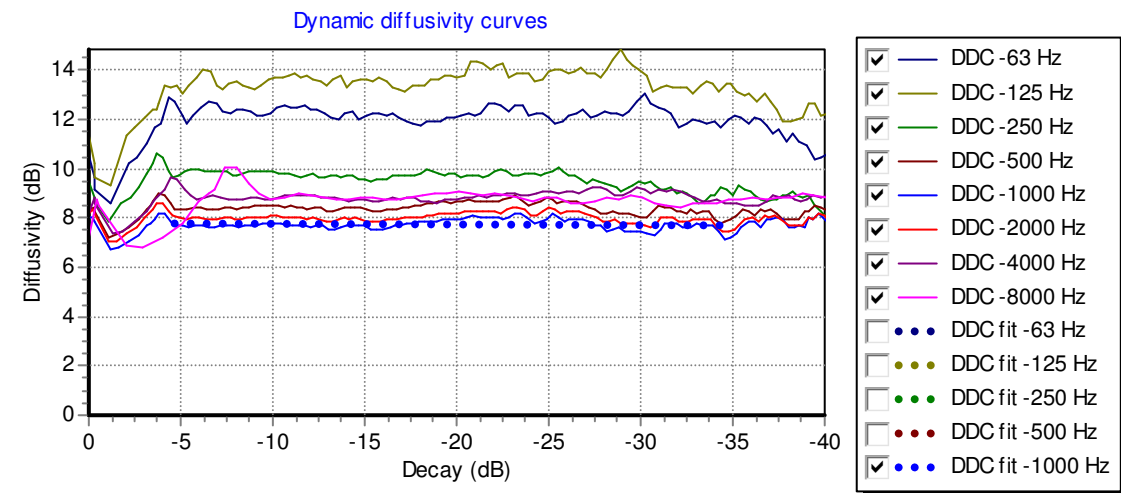
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# DDC and flutter echo

Before treatment with scattering surfaces



After treatment with scattering surfaces

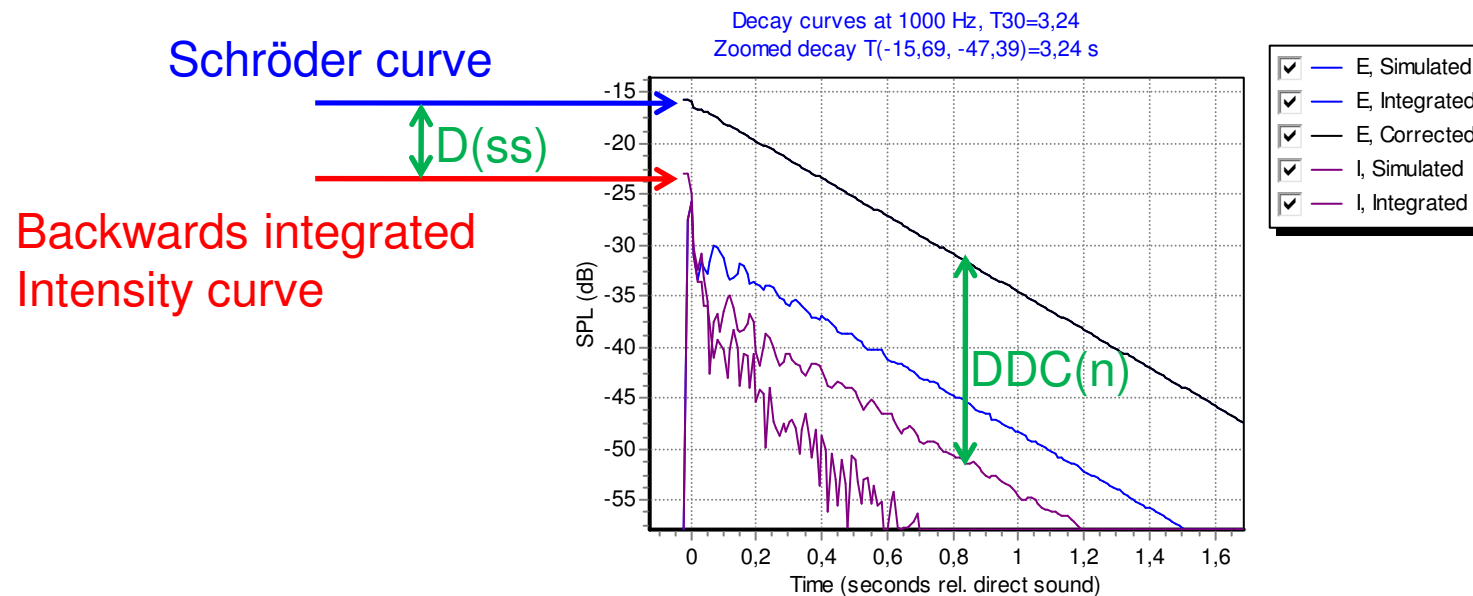


## Conclusions

- Dynamic Diffusion Curve DDC is suggested for investigating dynamic behavior of diffusion during decay
- Features for rooms without echoes;
  - Starts with Steady State Diffusion – in auditoria 2-7 dB,
  - Peak value typically within first 5-10 dB of decay
  - Plateau level (rev. diffusion) – in auditoria 5-12 dB
- Features for rooms with echo problems, e.g. flutter echo;
  - Ripples (xx dB?)
- Further research, optimum values, JND's, better tools than DDC?, extract other information from the DDC etc...

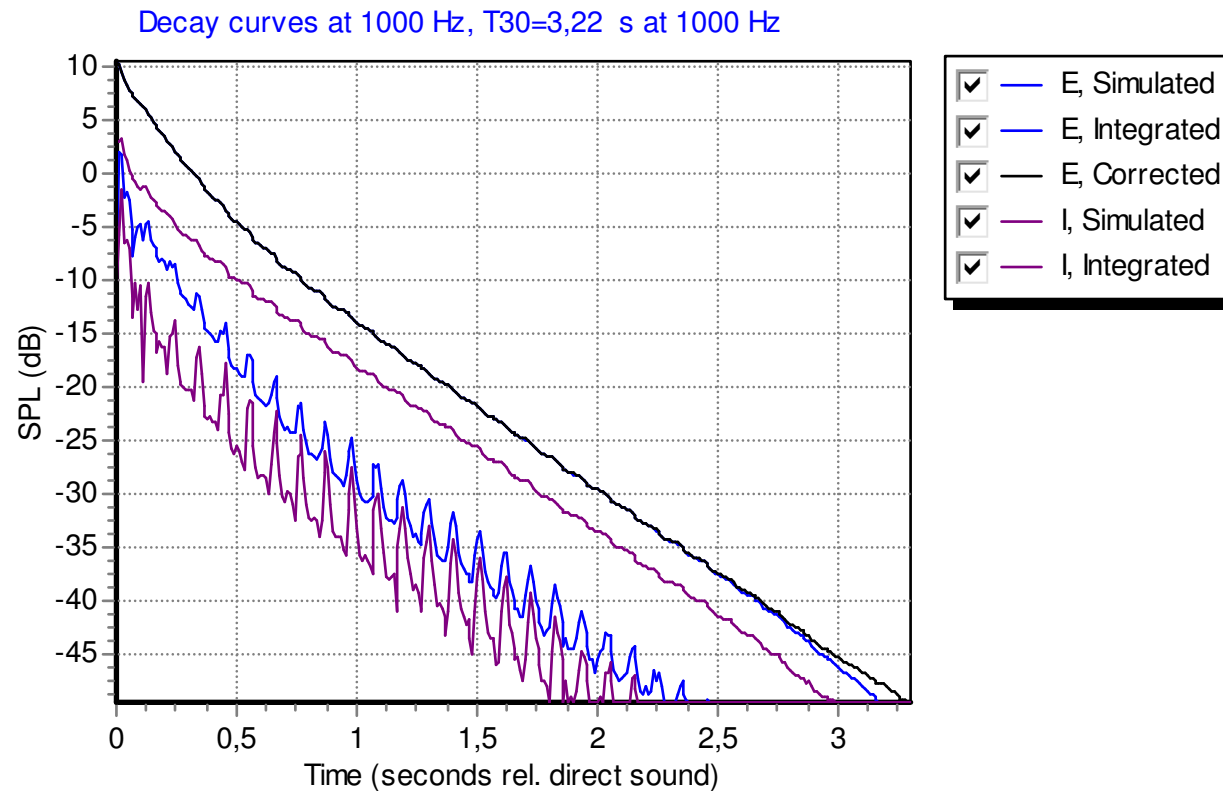
# Example

## Integrated energy and intensity curves



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# Integrated energy and intensity curves



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